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RELATIONS AMONG LOUDNESS, LOUDNESS LEVEL, AND SOUND-PRESSURE LEVEL

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16. Abstract

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SUMMARY

Formulas are given which relate the loudness, loudness level, and sound-pressure level of pure tones, hence of a band of steady noise that does not exceed the critical bandwidth. The formulas apply continuously over most of the acoustic regime and contain no undetermined coefficients.

REVIEW

Loudness is defined as the magnitude of the auditory sensation produced by an acoustic stimulus. A quantitative loudness scale has been established from subjective loudness judgments. Because the range of judged loudnesses is very large, it is convenient to adopt a logarithmic measure of loudness and designate it as the loudness level (ref. 1). The presently accepted empirical formulas (refs. 2 and 3) relating the loudness $\mathscr{L}_1$, loudness level L_1, and free-field sound-pressure level S_1 of a 1-kilohertz plane, progressive wave incident frontally are, effectively,[1]

$$L_1 = S_1 = 30 \log \mathscr{L}_1 + 40 \tag{1}$$

where L_1 is in phons (decibels), S_1 is in decibels, and $\mathscr{L}_1$ is in sones. Specifically,

$$S_1 = 10 \log\left(\frac{\tilde{p}_1^2}{\tilde{p}_0^2}\right) \tag{2}$$

[1]The coefficient of $\log \mathscr{L}_1$ is based on Stevens' latest estimate (ref. 4), namely 1/3, of the value of the exponent in eq. (3) of this report. In refs. 2 and 3 the coefficient is assumed to be 33.3.

where $\widetilde{p_1^2}$ is the mean-square pressure of the 1-kilohertz tone taken over the auditory integration (rather than infinite) time (≈0.2 sec), and $\left(\widetilde{p_0^2}\right)^{1/2} = 2\times10^{-5}$ newton-meter^{-2} is an accepted standard reference pressure. The unit of loudness (1 sone) is defined as the loudness of a 1-kilohertz progressive, plane wave, incident frontally, and possessing a sound-pressure level of 40 decibels in the free field. The loudness and sound pressure are empirically related by the power law

$$\mathscr{L}_1 = k_1\left(\widetilde{p_1^2}\right)^{1/3} \tag{3}$$

where k_1 is a dimensional loudness-transmission coefficient. Equation (3) is consistent with equations (1) and (2). Knauss proposed an equation similar to equation (3) in 1937 with $\widetilde{p_1^2}$ replaced by intensity (ref. 5). The ear responds, however, to sound pressure rather than intensity. S. S. Stevens noted this and let the word "intensity" refer, effectively, to mean-square pressure (ref. 6). The fact that the appropriate integration time should be the auditory integration time has apparently not been mentioned previously in the present context. (This factor should ultimately be significant for loudness at frequencies comparable to or less than the reciprocal of the auditory integration time.)

For a number of other discrete frequencies, Robinson and Dadson expressed the loudness level as a quadratic polynomial function of the sound-pressure level and tabulated the polynomial coefficients (ref. 7).

If, for any tone, the predicted loudness $\mathscr{L}$ and loudness level L are to have psychophysical significance, they both should be defined so as to vanish for the same value of the sound pressure for which the judged loudness vanishes. The loudness of any tone vanishes at a nonvanishing sound pressure. The loudness threshold presumably corresponds to the threshold of hearing (ref. 7) and is arbitrarily taken as 2×10^{-5} newton-meter^{-2} for a 1-kilohertz progressive, plane wave incident from the front. It is noteworthy, however, that careful tests by 110 observers with "normal" hearing indicated an average threshold level 4 decibels above this value (ref. 7).

Whatever the selected loudness threshold, it is apparent from equations (1) and (3) that neither the predicted loudness level nor the loudness vanishes anywhere near the sound pressure for which the judged quantities vanish (threshold). In this report, more accurate equations are proposed to remedy this deficiency and extend the formulation relating sound pressure and loudness to any pure tone throughout the acoustic regime, except, possibly, very near the boundaries of the regime. The proposed formulas contain no undetermined coefficients (cf. ref. 7), so that for a given source, the loudness and loudness level can be predicted from knowledge of the sound-pressure levels and tone frequency alone.

ANALYSIS

In addition to the fact that the loudness sensation is a function of sound pressure and frequency, the magnitude of the sensation also depends on the source-observer geometry (e.g., point or extended source and direction of incidence) and the method of listening (e.g., monaural or binaural and direct or with earphones). These "external" (preceding the eardrum) factors can be separated from the "internal" (succeeding the eardrum) contribution of the auditory system. This separation is convenient because, for a given source, the internal contribution is, effectively, a function only of the sound pressure and frequency. This automatically simplifies any theoretical analysis of the entire system. Because of the possible variability in response caused by changing the external factors, a progressive, plane wave incident frontally is a widely accepted form of exposure and, hence, in accompaniment with binaural listening and the availability of data for this circumstance provides a suitable reference condition. Equations (1) and (3) apply for this condition if the sound-pressure level S_1 is well above (say 40 db above, or more) the threshold of hearing. Finally, it is convenient to consider, first, exposure to a 1-kilohertz tone stimulus and then to relate the magnitude of the loudness sensation induced by any other tone to that induced by the 1-kilohertz tone.

Loudness of 1-Kilohertz Tone

If intensity is replaced by mean-square pressure, then it can be said that Knauss (ref. 5) recognized that loudness judgments - reported by Fletcher and Munson - of a 1-kilohertz tone heard through earphones were accurately represented by equation (3) for sound-pressure levels greater than 40 decibels. However, for loudnesses near the hearing threshold the loudness and mean-square pressure appeared to Knauss to satisfy a linear relation. The two formulas were synthesized into a more general formula (ref. 5) equivalent to

$$\mathscr{L}_1 = 10^{25/9} k_1^{1/3} \widetilde{p_1^2} \left(10^{25/6} k_1^{-1} \widetilde{p_1^2} + 1\right)^{-2/3} \tag{4}$$

If the difficulty of making relative loudness judgments near the threshold is considered, then it must be recognized that equation (4), exhibited in figure 1 with $\widetilde{p_1^2}$ expressed in decibels, fit the data well (ref. 5). Unfortunately, like equation (3), equation (4) indicates incorrectly that the loudness vanishes when the sound pressure vanishes. This might lead to theoretical difficulties. Subsequently, in 1955, S. S. Stevens reviewed a large collection of published loudness judgment data and concluded that equation (3) was essentially valid over the range of the data (ref. 6). Equation (3) cannot be correct near the threshold. Scharf and J. C. Stevens (ref. 8) found that their data were fit by the formula

$$\mathscr{L}_1 = k_1\left(\sqrt{\widetilde{p_1^2}} - \sqrt{\widetilde{p_0^2}}\right)^{0.6} \tag{5}$$

(Note that eq. (5) is not equivalent to $\mathscr{L}_1 = k_1\left(\widetilde{p_1^2} - \widetilde{p_0^2}\right)^m$ with m a constant, as implied in ref. 8.) In equation (5) the loudness $\mathscr{L}_1$ vanishes at the reference sound pressure p_0, as desired. Equation (5) (with $\widetilde{p_1^2}$ expressed in decibels) is plotted in figure 1 for comparison with equation (4). As an alternative to equation (5), Lochner and Burger (ref. 9) proposed that

$$\mathscr{L}_1 = k_1\left[\left(\widetilde{p_1^2}\right)^n - \left(\widetilde{p_0^2}\right)^n\right] \tag{6}$$

which, for $n = 0.27$, closely fit loudness judgment data obtained by Hellman and Zwislocki.

Let $n = 1/3$. Then, equations (5) and (6) are very similar in that, in both, $\mathscr{L}_1$ vanishes if $\widetilde{p_1^2} = \widetilde{p_0^2}$; equation (3) (with a slight discrepancy in the value of the exponent) is obtained in the high-sound-pressure limit; and the functional relations between $\mathscr{L}_1$ and $\widetilde{p_1^2}$ are very similar. Equation (5) implies a shift of the origin of the physical scale (rms pressure), whereas equation (6) implies a shift of the origin of the psychological scale (loudness). From the mathematical standpoint, equation (6) is more convenient than equation (5) in formulating a general theory of loudness. As shown in figure 1, the curve obtained from equation (6) with $n = 1/3$ falls very near the data representations proposed by Scharf and J. C. Stevens (ref. 8) and Lochner and Burger (ref. 9). None of these newer data are adequately represented by equation (4).

Whereas equation (4) has no obvious physical basis, equations (5) and (6) do have different physical implications. Specifically, the mechanical part of the auditory system is essentially a linear system (ref. 10), whereas the nervous system is certainly nonlinear in the sense that the physical correspondent of the mathematical exponents 0.6 and n is first detected in the nervous system (refs. 11 and 12). Therefore, equation (5) implies that a small fixed part of the average power input $\propto\widetilde{p_1^2}$ to be transmitted to the brain is dissipated or masked by internal noise in the mechanical system ahead of the nervous system. This dissipated, or masked, signal becomes ineffective in contributing to loudness. On the other hand, equation (6) implies that the ineffective portion of the signal is dissipated or masked primarily in the nervous system. Psychophysiological evidence may serve as a guide for choosing the more reasonable formula. In particular, cerebrally evoked activity in response to subliminal percutaneous electrical stimulation has been observed (ref. 13). In other words, the brain can be stimulated by external stimulants at magnitudes insufficient to produce a psychophysical response. Assume that cerebrally evoked activity is also obtainable from subliminal stimulation of the auditory system. To be observed (by electroencephalography) in association with the nervous system, the subliminal signal must be transmitted through, rather than dissipated or masked in, the mechanical system. The absence of a subjective response to this nervous stimulation would imply that the significant dissipation or masking must occur in the nervous system. Therefore, existing psychophysiological evidence, though inconclusive, suggests that equation (6) may be more reasonable than equation (5).

Combining the definition $L_1 = S_1$ with equations (2) and (6) and recalling that $\mathscr{L}_1 =$ 1 sone for $S_1 = 40$ decibels result in

$$L_1 = 30 \log(\mathscr{L}_1 + 0.0487) + 39.375 \tag{7}$$

Equation (7) resembles equation (1) and tends to the same values for sound-pressure levels greater than 40 decibels. However, equation (1) yields the unlikely value $L_1 = -\infty$ for $\mathscr{L}_1 = 0$, whereas equation (7) is in reasonable agreement with judged loudnesses as the loudness threshold is approached. Both curves are shown in figure 1.

Loudness of Other Tones

Formulas for other tones must, of course, be compatible with empirical auditory response curves. The exact form of the response curves depends on the external factors previously mentioned. For pure tones presented as plane, progressive waves incident frontally, the external factors can be separated mathematically from the internal contribution of the auditory system by using published data. Most published equal-loudness-level curves implicitly include both the external and internal factors. However, Wiener and Ross (ref. 14) measured only the external, power-transmittance-level function T_e associated with progressive waves and various azimuth angles. This function is given by

$$T_e = 10 \log\left(\frac{\widetilde{p_e^2}}{\widetilde{p^2}}\right) \tag{8}$$

where $\widetilde{p^2}$ is the mean-square sound pressure of the pure tone, plane, progressive wave in the free field, and $\widetilde{p_e^2}$ is the mean-square sound pressure of the same tone at the eardrum. Both $\widetilde{p_e^2}$ and T_e are functions of frequency and of the extent and orientation of the source relative to the listener. The external, power-transmittance-level T_e is plotted for frontal incidence as a function of frequency in figure 2 and listed in table I. (The curve shown in fig. 2 is not a duplicate of that given in fig. 5 of ref. 14, but rather, represents a judgment based on data in both refs. 7 and 14.) Note that $T_e = 1$ for a 1-kilohertz tone, so that the sound pressure at the eardrum is assumed to equal that in the free field. For other frequencies, $T_e > 0$, so that the outer ear serves to amplify the sound.

For pure tones and frontal incidence, Robinson and Dadson determined equal-loudness-level curves for the entire auditory system exposed to plane, progressive waves (ref. 7). In principle, these curves are obtained by subjectively equating the loudness of any given tone to that of a 1-kilohertz reference tone and then measuring the free-field, sound-pressure level of each tone. Note that, although the sound-pressure level

$$S = 10 \log\left(\frac{\tilde{p}^2}{\tilde{p}_0^2}\right) \tag{9}$$

is measured in the free field, only the sound pressure p_e at the eardrum is effective in producing loudness. This results because loudness is a psychophysical attribute of the internal auditory system alone. The sound pressure p_e corresponds to the sound-pressure level

$$S_e = 10 \log\left(\frac{\tilde{p}_e^2}{\tilde{p}_0^2}\right) \tag{10}$$

at the eardrum. From equations (8) to (10), it follows that

$$S_e = S + T_e \tag{11}$$

which expresses S_e as a function of the easily measured quantity S and the empirically known quantity T_e (fig. 2). If equation (11) and the data in figure 2 are used to re-express Robinson and Dadson's equal-loudness-level curves in terms of S_e, the result consists of equal-loudness-level curves referred to the internal auditory system beginning at the eardrum. In these curves (not shown) the oscillations of the Robinson-Dadson curves at high frequencies are eliminated. Moreover, these curves and the subsequent inverted and normalized representation are independent of the source-observer geometry and method of listening. Loudness-transmittance-level curves are obtained by inverting the internal, equal-loudness-level curves and normalizing the results relative to the loudness level at 1 kilohertz. The loudness-transmittance-level curves are shown un-normalized in figure 3 and normalized relative to levels at 1 kilohertz in figure 4. The normalized loudness-transmittance level N in figure 4 is defined by

$$N = 10 \log \frac{\mathscr{L}}{\mathscr{L}_1} \tag{12}$$

where $\mathscr{L}$ is the loudness of any given tone introduced at the same sound-pressure level S_e at the eardrum as that of the 1-kilohertz reference tone. (Recall that S_e is easily evaluated using eq. (11) and table I, or fig. 2.) It is apparent from figure 3 that, for any tone, the loudness level L is given by

$$L = S_e + N \tag{13}$$

However, by virtue of equation (11),

$$L = S + T_e + N \tag{14}$$

which expresses the loudness level of any tone in terms of easily measured and known quantities.

Although the function N is a fixed characteristic of the internal auditory system, it has, thus far, only been exhibited graphically. However, a formula has been devised which, unlike the Robinson-Dadson polynomial representation (ref. 7), continuously fits the loudness-transmittance-level function N quite well over most of the audible range and does not involve unknown constants.

Thus, let $\omega_1/2\pi$ and $\omega_2/2\pi$ designate, respectively, lower and upper cutoff frequencies, and $\omega_m/2\pi$ the geometric-mean frequency of the function N. Then, N is given approximately by the formula

$$N = 60 \log\left\{\left(\frac{\omega}{\omega_m}\right)^2 \left[1 + \left(\frac{\omega_m}{\omega_1}\right)^2\right]\left[1 + \left(\frac{\omega_m}{\omega_2}\right)^2\right]\left[1 + \left(\frac{\omega}{\omega_1}\right)^2\right]^{-1}\left[1 + \left(\frac{\omega}{\omega_2}\right)^2\right]^{-1}\right\} \tag{15}$$

where

$$\frac{\omega_1}{2\pi} = \text{antilog}\,(-0.005706\, S_e + 2.1761)$$

$$\frac{\omega_2}{2\pi} = 18\,000 \qquad (\text{independent of } S_e)$$

$$\frac{\omega_m}{2\pi} = \frac{(\omega_1\omega_2)^{1/2}}{2\pi}$$

Equation (15) is the simplest formula found which would fit the data, would represent (aside from the logarithm) a low-pass and high-pass filter in series (as expected of the auditory system), and could be easily manipulated in a theory of loudness (ref. 15). (Eq. (15) is a modification of the formula for listening with earphones given in ref. 15. Eq. (15) is, of course, for direct listening and frontal incidence.)

Equation (14) permits computation of the loudness level L of any tone from its measured sound-pressure level S in the free field. The loudness $\mathscr{L}$ of any tone can also be calculated from knowledge of its free-field sound-pressure level S. Thus, if S is measured, N can be found by using equation (11), figure 2 (or table I), and equation (15) (or fig. 4). Then, $\mathscr{L}$ is given by

$$\mathscr{L} = \mathscr{L}_1 \text{ antilog } \frac{N}{10} \tag{16}$$

where

$$\mathscr{L}_1 = 0.0487\left(10^{S_e/30} - 1\right) \tag{17}$$

follows from equations (6) and (2) and the selected reference values. Finally, the loudness and loudness level are related by

$$L = S + T_e + 10 \log \frac{\mathscr{L}}{\mathscr{L}_1} \tag{18}$$

or, alternatively, by

$$\mathscr{L} = \mathscr{L}_1 \text{ antilog } \frac{(L - S - T_e)}{10} \tag{19}$$

which result by combining equations (12) and (14). Note that in these equations, as in equation (12), $\mathscr{L}$ and $\mathscr{L}_1$ are determined for the same sound-pressure level S_e at the eardrum.

The preceding development is concerned with plane waves at frontal incidence. The function T_e is given for other angles of incidence in reference 14. A correction of the function T_e for the case of a diffuse noise source is presented in reference 16. This correction has been incorporated in T_e, and the resultant modified function T_e is listed in table I and presented graphically in figure 2.

The sound pressure and loudness of any steady noise possessing a bandwidth less than the local critical bandwidth may be equated to those of a pure tone at the geometric-mean frequency of the band. Hence, the preceding formulas apply not only for a pure tone but also for a band of noise which does not exceed the local critical bandwidth.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, January 14, 1971,
129-01.

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TABLE I. - EXTERNAL, POWER-TRANSMITTANCE-LEVEL FUNCTION

One-third octave band midfrequency, Hz	Plane wave incident frontally	Diffuse field
	External, power-transmittance level, T_e, db	
<160	0	0
160	.5	.5
200	1	1
250	1.5	1
315	2	1
400	2	.5
500	2	0
630	1.5	-1
800	.5	-2
1 000	0	-2.5
1 250	0	-2
1 600	1.5	0
2 000	4	3.5
2 500	7	7.5
3 150	10	11
4 000	12	12.5
5 000	10	8.5
6 300	6	2
8 000	0	-5
10 000	2	-1
12 500	9	9
16 000	5	----
20 000	0	----

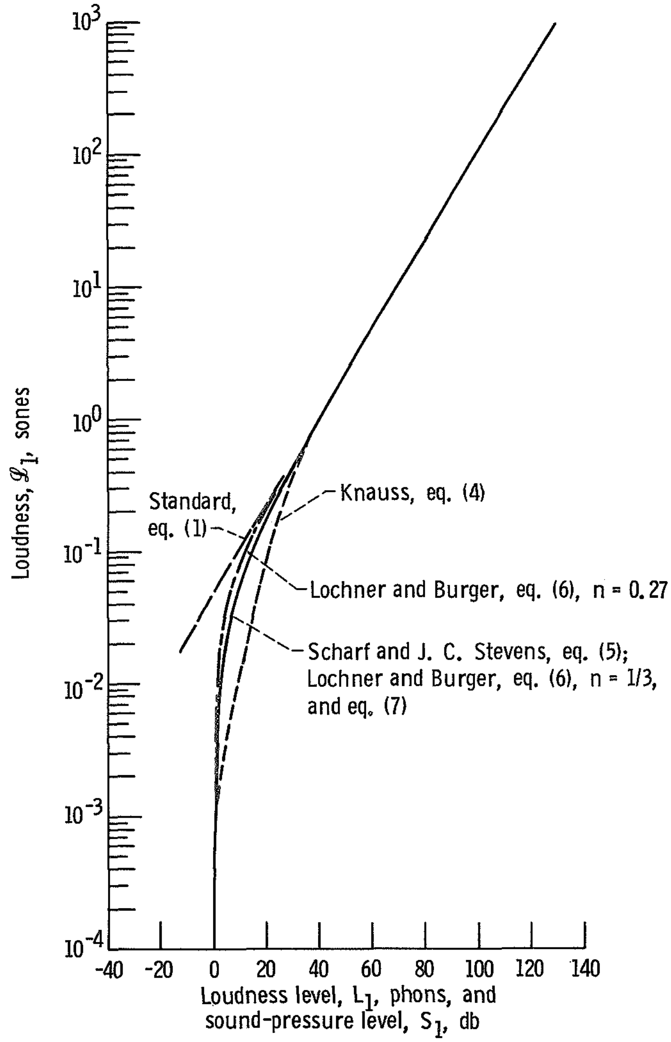

Figure 1. - Relations among loudness, loudness level, and sound-pressure level for 1-kilohertz tone.

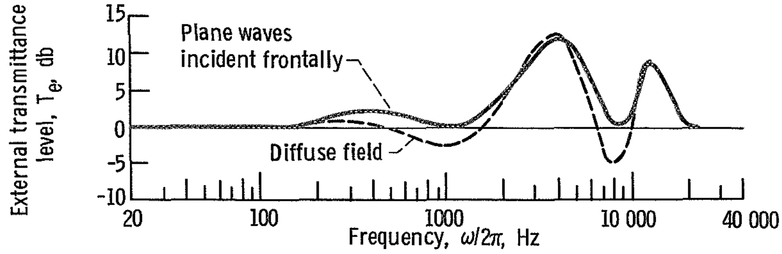

Figure 2. - External, power-transmittance level, T_e = 10 log (mean-square pressure at eardrum/mean-square pressure in free field).

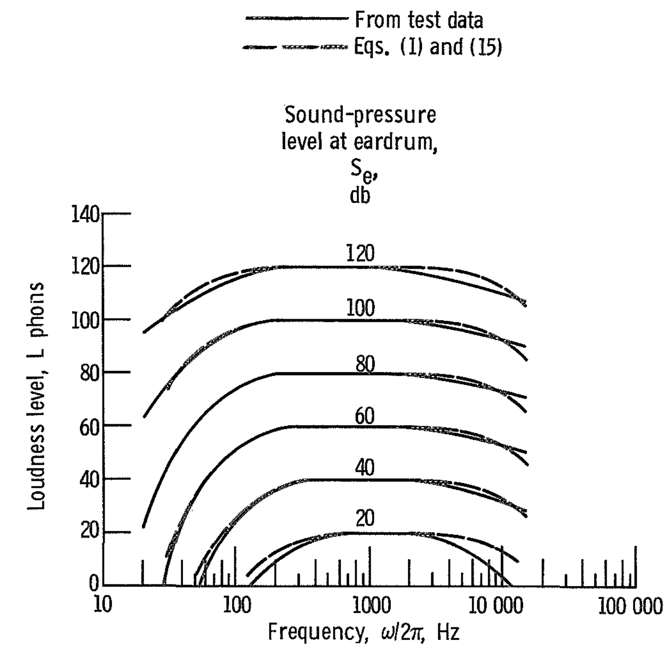

Figure 3. - Internal, loudness-transmittance level (un-normalized).

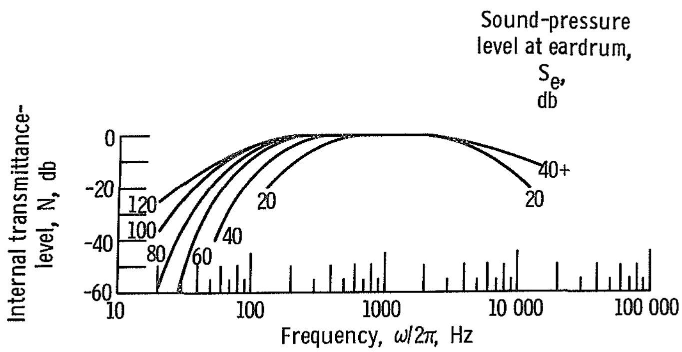

Figure 4. - Internal, loudness-transmittance level (normalized).

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